dehiscence, and shortened grain-filling duration (Shrestha et al., 2022). Night-time warming further elevates respiration, accelerates senescence, and contributes to yield penalties estimated at several percent per °C increase above critical thresholds, with reported yield declines of about 4-5% per 1 °C rise beyond 27 °C and up to 41% reduction by 2100 under projected high night temperatures (El-Mageed et al., 2022).

2.3 Effects of water management on rice growth

Water availability and irrigation strategies strongly influence both biomass production and yield components in rice. Under drip irrigation and mulching, progressive water stress at tillering reduces chlorophyll content, leaf photosynthesis, and final tiller number, leading to fewer effective panicles, lower seed-setting rate, and reduced thousand-grain weight, although moderate stress can substantially increase water-use efficiency relative to flooding (Xu et al., 2020). Field experiments with aerobic varieties show that mild water-saving irrigation (~20% less water than conventional) can enhance antioxidant activity, maintain photosynthesis, increase harvest index, and significantly improve grain yield and quality, indicating a non-linear response of growth and yield to water deficit intensity (Gao et al., 2024).

Across broader environments, meta-analysis of water-saving irrigation practices (controlled, intermittent, shallow-wet, AWD) reveals consistent increases in water productivity (4.7%-14.3%) relative to traditional flooding, with variable effects on yield depending on system, soil, and climate. Alternate wetting and drying regimes typically save 17%-34% of irrigation water and can increase or only slightly reduce yield, yielding higher water productivity, while continuous flooding maximizes yield but at the cost of much greater water consumption (Mboyerwa et al., 2021; Roushan et al., 2023). These quantitative relationships between water regime, evapotranspiration, yield components, and water productivity form a critical foundation for modeling grain yield under diverse water management scenarios.

3 Temperature and Water Interactions in Rice Production

3.1 Synergistic effects of temperature and soil moisture

Temperature and soil moisture interact strongly to determine rice yield, with compound extremes often causing larger losses than either stress alone. A panel analysis of rainfed and irrigated rice in India (2000-2018) showed that excessive heat markedly reduced yield, and that losses were greatest when high temperatures coincided with low soil moisture; in contrast, high soil moisture partly offset heat damage, underscoring the importance of managing root-zone water to buffer thermal stress (Mishra et al., 2024). A global empirical assessment similarly found that models using root-zone soil moisture, rather than precipitation, explained much more interannual yield variation and revealed that soil moisture and temperature contribute roughly equally to historical yield fluctuations, highlighting the need to explicitly represent both drivers in yield formation models (Proctor et al., 2022).

These synergistic effects arise because water status controls canopy cooling, stomatal conductance, and thus plant temperature under heat stress. Field experiments with super hybrid rice showed that as water supply was reduced from shallow flooding to mild and severe water stress, canopy relative humidity and plant-atmosphere and soil-atmosphere temperature differences declined, and grain yield fell by up to ~35%, with positive correlations between temperature differentials and yield (Meng et al., 2020). Long-term field data from Taiwan indicated that climate-change-induced increases in water-deficit stress, quantified via crop water status across growth stages, have increasingly constrained rice growth in recent decades, particularly during developmental stages, confirming that water deficits and warming jointly shape yield trajectories over time (Chen et al., 2023).

3.2 Stress responses under extreme climate conditions

Extreme hot-dry or cold-wet events are projected to become more frequent and can sharply disrupt grain yield formation. A global analysis for 1980-2009 showed that co-occurring extremely hot and dry events consistently reduced yields of major crops, including rice, worldwide, with probabilities of such compound extremes increasing over time (Heino et al., 2023). A review of compound heat and moisture extremes reported that hot droughts since about 2000 have been linked to yield losses up to 30% in key breadbasket regions, and that interactions among plant physiology, soil-plant-atmosphere water fluxes, and climate dynamics complicate prediction of net yield impacts under future compound extremes (Lesk et al., 2022).